A SPECIES' TRAIT BASED APPROACH TO CLIMATE CHANGE VULNERABILITY ASSESSMENT IN NORTH SEA FISHERIES SPECIES

A Thesis

by

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ABSTRACT

Scientists are continuously developing new methods to project the impacts of climate change. Various consequences of climate change have already been observed in terrestrial and marine environments, such as those affecting geographic range location and boundaries, body size, life history, and phenology. Extant models often estimate a species' bio-climate envelope (the specific conditions for a viable population) on which an estimated environmental shift due to climate change is imposed in order to estimate potential re-distribution of the species' range. However, traditional bio-envelope models may underestimate species' vulnerability to climate change. By contrast, the Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change (ICFARECC) approach suggests that species traits known from first principles are better able to estimate a species' vulnerability to climate change. My objective was to apply the ICFARECC framework to a complex but intensively-studied marine ecosystem, the North Sea. I evaluated ICFARECC strengths, limitations, and ability to provide distinctive information by comparing ICFARECC findings to the existing IUCN approach. I analyzed primary literature and public governmental reports to collect the data needed for 20 dominant North Sea fisheries species from which I was able to obtain 57% of the data required for the ICFARECC framework. ICFARECC analysis indicated that most North Sea fisheries species are not very vulnerable to climate change. Moreover, I found that the ICFARECC vulnerability scores were not correlated to extant IUCN criteria, suggesting that the two models provide distinct information. Data

availability varied per Category and species. The lack of physiological data in Category II may have resulted in an underestimation of climate change vulnerabilities. This study suggests some improvements to the framework, including adjustments to the terminology of criteria and thresholds and suggestions for a new format to make the framework more user-friendly.

To mom & dad, I would not have gotten here without you.

To Shanice, may this inspire and motivate you.

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Joseph Bernardo from the Biology Department at Texas A&M University and fellow researchers Jennifer E. Buhay, Kelly Zamudio, Keith A. Crandall, Suzanne Estes, Matthew P. Hare, Ary Hoffmann, Jeffrey A. McNeely, Jonathon H. Stillman, Salvatore J. Agosta, and Hans-O. Pörtner developed the ICFARECC framework used in this project.

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NOMENCLATURE

ENM	Environmental Niche Models
ICES	International Council for the Exploration of the Sea
ICFARECC	Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change
IPCC	Intergovernmental Panel for Climate Change
IUCN	International Union for Conservation of Nature
NS	North Sea
SST	Sea Surface Temperature

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1. INTRODUCTION

Rising temperatures associated with climate change have affected the structure and composition of diverse communities. The Intergovernmental Panel on Climate Change (IPCC) projects that climate change will continue to increase global temperatures over the next decades (IPCC, 2014). Studies have shown effects of climate change on species' range position and margins, body size, life history, phenology, as well food web dynamics, species interactions, community structure, and thus ecosystem function (Crick and Sparks, 1999; Edwards and Richardson, 2004; O'Brien et al., 2000; Parmesan, 2006; Parmesan and Yohe, 2003; Poloczanska et al., 2013; Pörtner and Knust, 2007; Walther et al., 2002). However what remains unclear is the extent of the abovementioned effects, whether these effects will become more pronounced over time, and the time frame over which this might occur.

1.1. Climate Change in Marine Systems

A wide array of effects of climate change has been reported for marine systems, including in the well-studied North Sea, the focus of this study (Burrows et al., 2011; García Molinos et al., 2016; Stuart-Smith et al., 2015) These include range shifts of many fishes (Dulvy et al., 2008; Pörtner et al., 2008; Pörtner and Knust, 2007), invertebrates (Helmuth et al., 2006; Hiddink et al., 2015; Schiel et al., 2004), large marine predators (Worm and Tittensor, 2011) and other vertebrate species. Responses of marine organisms to climate change have far-reaching implications for both

economically important fisheries as well as community structure (Hiddink and Ter Hofstede, 2008) and various ecosystem services (Worm et al., 2006). For example, although European cod (*Gadus Morhua)* stocks have declined due to overexploitation, these effects have been exacerbated due to the climate-induced changes in plankton biomass (Brander, 2005; Roessig et al., 2004).

The specific mechanisms causing climatic changes in the North Sea are unclear (Roessig et al., 2004). Evidence suggests that the North Atlantic Oscillation (NAO) exerts a strong influence. Many efforts have been made to assess how marine biodiversity and ecosystems will respond to climate change, how resilient they may be, and subsequent implications for fisheries and other ecosystem services.(Brander, 2005; Brander, 2010; Cheung et al., 2009; Deutsch et al., 2015; García Molinos et al., 2016; Somero, 2010; Stuart-Smith et al., 2015). Efforts to assess how climate change will affect biodiversity and ecosystems have employed a variety of different approaches.

1.2. Phenomenological Approaches to Assessing Climate Change

To date, the dominant approach used to assess effects of climate change on species' abundances has been environmental niche modeling (ENM), also known as ''habitat suitability models'' or ''species distribution models" (Araújo and Peterson, 2012). ENMs estimate a species' bio-climate envelope, the specific conditions for a viable population, on which is imposed an estimated environmental shift due to climate change in order to estimate potential re-distribution of the species. ENMs are widely used because they provide a quantitative estimate, are intuitively appealing and

relatively easy to implement (Kearney and Porter, 2009; Thomas et al., 2004). Using bio-climate envelopes, Thomas et al. (2004) estimated that 18-35% of biodiversity will be lost by 2050 depending on the pace of climate change. Such predictions have increased concerns related to climate change. However, Thomas et al. (2004) acknowledged that bio-climate envelopes do not indicate absolute physical limits for species, but rather estimate their realized niches within a multi-species community.

Several studies have reviewed the advantages and limitations of ENMs (Davis et al., 1998; Guisan and Thuiller, 2005; Kearney and Porter, 2009; Pearson and Dawson, 2003), and a general consensus is that ENMs have limited predictive power because they estimate species' spatial distributions based only on environmental factors. Pearson and Dawson (2003) highlighted the disregard for interspecific interactions in ENMs. Davis et al. (1998) showed that interspecific interactions, such as predation, symbiosis and competition, can modify species distributions. Furthermore, ENMs ignore species' ability to adapt to the changing climate or to disperse to more suitable conditions, thus increasing the potential for leading to erroneous conclusions regarding species' response (Araújo and Luoto, 2007; Pearson and Dawson, 2003). For example, Thomas et al. (2001) showed how various insects in Britain expanded their habitats through selection for longer winged individuals (i.e. better dispersers).

There are several factors that limit the ability of ENMs, and other similar models and algorithms, to predict species distribution patterns under climate change. The presence of strong residual patterns in these models indicates the presence of various factors not represented by the model, such as genetics dispersal, or important

environmental factors (Dormann et al., 2007; Elith and Leathwick, 2009; Miller et al., 2007; Whitehead et al., 2001). Several of these factors are especially difficult to address in marine systems. For example, the presence of currents can make estimation of dispersal in marine systems challenging (Sundblad et al., 2011; Whitehead et al., 2001). Expert knowledge of an ecosystem's biotic and abiotic relationships are an important part of ENMs (Beger and Possingham, 2008; Garza-Pérez et al., 2004) making them more difficult to readily apply in marine systems.

Another method used to assess species' vulnerability to climate change is the International Union for Conservation of Nature (IUCN) red list assessments (RLA). The assessments assign species to categories of extinction risk (least concern, near threatened, vulnerable, endangered, critically endangered, extinct in the wild, and extinct) based on population trends and persistence that can be compared between different taxonomic groups. They are an important tool in conservation biology because they are widely applicable, simple to use and objective (Akçakaya et al., 2000). Although RLAs remain valuable, they were not designed to evaluate climate change impacts, but rather exploitation. They give an indication of the species current extinction risk, but do not provide information on potential future risk relating to climate change (Thomas et al., 2001).

Conservation management decisions are often based on studies using RLAs, ENMs or the similar species distribution model (SDM). Thus, it is often assumed that species that are widespread and have low habitat specificity will be less threatened in the face of climate change (Dunn, 2002; Possingham et al., 2002). However, various studies

have shown that widespread species can be or are threatened, even when general protective measures are taken (Gaston and Fuller, 2007).

1.3. An Alternative: Species' Traits-Based Approaches

As compared to the narrower focus of ENMs, more encompassing frameworks have been suggested in order to assess climate change-associated vulnerability (Foden et al., 2013; Hare et al., 2016; Thomas et al., 2011). Thomas et al. (2011) noted that existing vulnerability assessment approaches, such as the IUCN Red List, were not developed for climate change assessment, a serious limitation. These vulnerability assessments utilize data on a species' current and past range and observed trends in population size as a framework for effects of climate change. However, this framework limits species' future dispersal capabilities to those observed in the past. Similarly, Hare et al. (2016) advanced a framework for climate change vulnerability assessment of marine fish and shellfish species that utilizes data pertaining to current knowledge of species' biology, such as prey specificity, adult mobility and spawning cycle, to assess vulnerability.

Although possessing limitations, these alternative frameworks incorporate information from species' traits and therefore constitute a key advance over phenomenological modeling such as ENMs. Nonetheless, none of these approaches consider direct measures of species' physiology and population genetic data to examine species' potential to tolerate change, disperse or evolve in response to environmental variation.

1.4. Development of the Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change (ICFARECC)

There are three avenues of response to climate change: i) tolerate changing condition *in situ*; ii) shift the range to track climate conditions to which an organism is adapted or iii) evolve tolerance or dispersal capability. Without one or more of these avenues of response, a species will go extinct (Bernardo, 2011; Davis et al., 2005; Roessig et al., 2004). Species' traits-based approaches to assessing climate change vulnerability aim to characterize species' capacities that underlie these avenues of response.

In the context of climate change, scientists studying diverse taxa have identified a broad array of species' traits that are expected from first principles of ecology and evolution to be predictive as to how species will respond to climate change. First principles are described as "quantitative law-like postulates about processes underlying a given class of phenomena in the natural world with well-established validity, both theoretical and empirical (i.e., core knowledge)" (Marquet et al., 2014). Rijnsdorp et al. (2010) in the International Commission of the Exploration of the Sea (ICES) cooperative research report stated that a bottom up or first principles approach needed to be adopted in order to assess the potential effects of climate change on fisheries productivity and resources. Furthermore, they state that a quantitative conceptual framework needs to be developed to completely understand the possible responses of fish populations to climate change. The species' traits expected to predict climate change vulnerability include physiological tolerance (Bernardo et al., 2007; Bernardo and Spotila, 2006; Deutsch et

al., 2008; Hoffmann et al., 2003; Huey et al., 2012; Pörtner and Knust, 2007; Somero, 2010; Sunday et al., 2011, 2012; Sunday et al., 2014) and its plasticity (Kellermann et al., 2015; Stillman, 2003), dispersal ability (Bernardo et al., 2007; Davis and Shaw, 2001; Janzen, 1967) and evolutionary potential (Huey et al., 2012).

Several of these scholars were invited to a working group to develop a generally applicable, objective, and operational framework for assessing climate change vulnerability. The insights of the various scholars have been incorporated into "Integrative Conceptual Framework for Assessing Relative Endangerment due to Climate Change" (ICFARECC; Bernardo, Buhay, Zamudio, Crandall, Estes, Hare, Hoffmann, McNeely, Stillman, Agosta, and Pörtner, *in prep*). This framework uses intrinsic species' traits related to adaptive capacity in order to assess climate change vulnerability based on generalized criteria and thresholds for endangerment determined *a priori*. These species' traits are assessed through 27 criteria in four categories:

I. Ecological: Largely based on existing endangerment criteria concerning population size and trends and geographic range size
II. Physiological: Traits related to tolerance and capacity
III. Dispersal: Traits related to dispersal ability
IV. Evolutionary potential: Traits related to a species' ability to adapt or evolve

Bernardo et al. (*in prep*) have evaluated the relative importance of these criteria to each of the three response modes and proposed how these criteria might estimate species' vulnerability to climate change. Category I (ecological) encompasses criteria

that have been identified as relevant factors to vulnerability assessments and form the basis of IUCN Red List assessments (IUCN, 2015). These include various population measures such as population size, temporal trends and spatial distribution. These measures reflect contingencies about what contributes to rarity (Rabinowitz, 1981). Additional ecological criteria referring to patterns of species interactions, and other measures including latitudinal extent, have been added to this original IUCN criteria set.

Category II (physiological traits) includes thermal tolerance breadth, critical thermal limits and their plasticity, thermal optima, and the differences between current habitat temperature and both thermal optima and thermal limits. Criterion II.I Metabolic capacity, for example, was derived to assess species' thermally limited oxygen delivery. Portner and Knust (2007) showed that temperatures that limit oxygen delivery are closely related to temperatures beyond which growth performance and abundance are negatively influenced. This study suggested that thermally limiting oxygen delivery is likely to be indicative of climate change tolerance. Furthermore, the authors state that limited oxygen delivery will cause species to disperse to more suitable locations or go extinct.

Category III (dispersal) capabilities are characterized by direct measures (e.g., movement per unit time), with indirect measures estimated from population genetic structure, such as number of migrants or haplotype groups (Bernardo et al., *in prep*; Bernardo et al., 2007). Davis and Shaw (2001) contributed to the idea that insights into haplotypes within a region facilitate understanding of migration patterns.

Finally, Category IV (evolutionary potential) assesses genetic diversity of the species, including heterozygosity and nucleotide diversity. Heritability, additive genetic variance, and life history patterns may indicate species' evolutionary potential in light of climate change (Kellerman et al., 2009, Hoffman, 2010, Crozier and Hutchings, 2013, Bernardo et al., *in prep*).

Taken together, these measures provide a framework for the evaluation of a range of properties that are hypothesized to influence how species will respond to climate change. Although this approach has not been applied in a strictly marine environment, it has been successfully applied to several other ecosystems, such as animals exploited for subsistence by Inupiat subsistence hunters in the Arctic and for salamanders in the Appalachian Mountains (Bernardo, *in pers.comm.*).

1.5. Aims

ICFARECC is intended to be applicable across different species and ecosystems. This approach, unlike that of ENMs, accounts for traits related to species' current realized niche, in addition to traits related to how species will cope with changing conditions. In this thesis, I apply the ICFARECC framework to North Sea fisheries species as a meta-analysis to estimate how climate change might affect these species. My thesis focus is to test the feasibility of applying ICFARECC to the most extensively studied species in one of the world's most intensively studied fisheries with the objectives of identifying strengths and limitations of this framework. I compared the conclusions of the ICFARECC framework to assessments derived from the IUCN

metrics in order to evaluate how vulnerabilities might differ between these different methods. ICFARECC had not been tested on an exclusively marine system; my study provides the developers with an indication of the suitability of the framework to a marine system.

2. MATERIAL AND METHODS

2.1. Framework Application

The methods used in this thesis, including the development of the framework are described in Bernardo et al, *in prep*. I followed the following procedure to apply the ICFARECC method:

1) Species set and or potential regions of interest were identified.

2) An internet search was performed using Google Scholar, Scopus, and Web of Science to obtain published data (primary literature and student theses) on species' trait values related to measures utilized in the framework using various search terms (Table 1). The species' trait data were recorded on a worksheet (sample worksheets - Appendix A).

3) The species' traits were compared to preset threshold values determined by ICFARECC developers to assign vulnerability assessments as "-1" (not vulnerable), "0" (vulnerable) and "1" (highly vulnerable) on a worksheet. For example, sole (*Solea solea)* scored "-1" for criterion H in the physiological (II) Category, behavioral/phenological response because Teal et al. (2008) showed evidence that sole breeding timing shifted earlier at warmer temperatures. Moreover, Greve et al. (2005) showed a high correlation between sea surface temperature (SST) and early, middle and late season abundance. ICFARECC indicates that a species must show one of the following: "Microsite selection,

migratory and phenological tracking", "incomplete phenological shifts", or "no phenological shift" to score "-1", "0", and "1" respectively. Thus, sole was scored not vulnerable (-1).

4) After each criterion was scored I calculated the average score within each subset (Category) and criteria I.A – I.E (IUCN criteria). Thereafter I also calculated an overall vulnerability score by averaging the Category scores for each species. Each criterion weighed equally in the final calculation.

5) These subset average scores were compared to each other to analyze whether each Category provides unique information. Finally, I compared the IUCN-free ICFARECC scores compared to IUCN criteria to evaluate whether ICFARECC criteria provided distinct information.

Although I attempted to obtain data for all the traits for each targeted species, not all traits were available for all species. However, similarly to the IUCN approach, the IFARECC approach does not require data for all criteria in order to make an assessment.

Table 1. Examples of search terms used. These search terms were used in combination with species name. This is not an exhaustive list.

Ecological	"population trends" OR "population status" OR "extent of occurrence" OR "range area" OR "area of occupancy" OR "population size" OR "population trend" OR "population size" OR "population forecast" OR "population model" OR "range area" OR "range map" OR "altitudinal breadth" OR "altitudinal range" OR "diet" OR "ecological dependency"
Physiological	"critical thermal limits" OR "critical thermal maximum" OR "critical thermal minimum" OR "tolerance breadth" OR "pejus" OR "ambient temperature of region" OR "plasticity" OR "acclimation" OR "temperature" OR "optimum temperature " OR "habitat temperature" OR "temperature projection"
Dispersal	"mobility" OR "migration" OR "basal metabolic rate" OR "metabolic capacity" OR "metabolism" OR "dispersal" OR "telemetry" OR "isolation by distance"
Evolutionary potential:	"haplotype diversity" OR "heterozygosity" OR "genetic erosion" OR "alleles" OR "private haplotypes" OR "genetic diversity" OR "nucleotide diversity" OR "population genetics" OR "genetic structure" OR "skyline plot" OR "genetic history" OR "heritability" OR "evolvability" OR "genetic diversity" OR "diversity within species" OR "fecundity" OR "generation time" OR "effective population size"

2.2. Study System

The ICFARECC approach was applied to the North Sea. I considered the North Sea a good case study for a variety of reasons. The North Sea is 750 000 km and located near the United Kingdom, Norway, Denmark, Germany, the Netherlands, Belgium and France. It supports a diverse array of extensively studied invertebrates, fish, and marine mammals, as well as economically important fisheries. The implications of climate change affect decisions pertaining to conservation as well as management of these fisheries, whereas its coasts provide important nesting grounds for several species of fish-eating birds. Moreover, the North Sea provides a suitable habitat for primary producers and other lower trophic levels, which in return are able to support predators at higher levels (Dunnet et al., 1990). Examples of predators that appear to persist under exploitation are herring (*Clupea harengus*) and cod (*Gadus morhua*). Others, such as halibut (*Hippoglossus hippoglossus*) and tuna (*Thunnus spp.*) have not fared as well and have become rare or disappeared entirely due to exploitation (ICES, 2008). Moreover, models predict SST increases up to 3.0° to 3.9°C in the shallower southern North Sea, accompanied by sea level rises of up to 68 cm by 2050 (Kundzewicz & Parry, 2001).

2.3. Species Selection

A species list was compiled based on fisheries catch data from International Council for the Exploration of the Sea (ICES), which identified the top 20 fisheries species for my study (ICES, 2011). These data were extracted from the complete ICES historical nominal catches by selecting locations IIIa +IVa, b +c. This location selection includes the North Sea (IVa, b + c; from the Shetland Islands down to the Strait of Dover), Skagerrak, and Kattegat (IIIa). Data for Skagerrak and Kattegat are being included as these areas are suggested to function as nursery grounds for North Sea species (Svedäng et al., 2007). Catches in tonnes for each species in locations IIIa +IVa, b +c were summed over the available time period. The final list included 20 fish species with catches in tonnes in the North Sea over the years 1950 to 2010.

2.4. Approach to Qualitative Criteria Thresholds

Specific thresholds needed to be adjusted for this project given that the framework has never been applied to exclusively marine fish. These included the I.G: altitudinal breadth, II.I: metabolic capacity, and IV.A.1: heterozygosity. Altitudinal breadth was adjusted because previous thresholds related specifically to terrestrial species. I re-defined the altitudinal breadth as depth. The new thresholds were based on the availability of light and the constancy of temperature in the ocean. The most vulnerable layer was considered to be the photic zone (≤200 m). Light is able to penetrate this layer and temperature is likely the most variable in this zone. Species that live in this zone such as whiting (*Merlangius merlangus*) were scored highly vulnerable

("1") based on this criterion. Species that are able to survive and thrive in the deepest depths of the aphotic zone (≤1000), such as Atlantic Horse Mackerel (*Trachurus trachurus*), will likely be least affected by surface temperature changes and thus were scored not vulnerable ("-1). Survival of some species lies in between these extremes (200-1000 m) and was scored vulnerable/neutral ("0").

In order to score the metabolic rates consistently, quantitative measures were established. The thresholds established for metabolic rate, specifically aerobic scope, were qualitative (high, medium, low) rather than quantitative. Killen et al. (2016) published various measures of metabolic scope for teleosts. Their data were used to establish quantitative measures. Their lower quartile and upper quartiles were used to represent the ICFARECC "not vulnerable" and "highly vulnerable" cutoffs respectively. The thresholds were <121, 121- 340, and >340 for "1", "0" and "-1" respectively.

Preferably, other thresholds for the analysis are established experimentally in the manner in which the thresholds for metabolic rate were established. For example, ICFARECC uses heterozygosity in presumptively neutral marker loci (that is, not necessarily for loci that are directly linked to climate change tolerance) as a measure of genetic diversity in the species. Genetic diversity has been shown to have a positive effect on population fitness (Reed and Frankham, 2003). There was no comprehensive dataset containing heterozygosities for fish. So, available values for heterozygosity were simply divided into quartiles. The resulting thresholds for heterozygosity resulted into <0.25 for "1", 0.25 – 0.75 for "0" and >0.75 for "1".

2.5. Category Comparisons

I collected available RL assessments from the Red List website (IUCN, 2015). RL assessments were not available for most species, either because the species had not been assessed, (e.g. cusk, *Brosme brosme*), or the assessment was outdated (e.g. haddock, *Melanogrammus aeglefinus,* was last scored in 1996, similarly to cod, *Gadus morhua).* Sole (*Solea solea)* was scored "data deficient" by the IUCN. I rescored all ecological criteria, including the IUCN criteria, for each species independently from the IUCN in order to ensure the data were current and to manage/reduce experimental error. I assumed that there might be a scoring error and that this error would be amplified when species are assessed by different evaluators. IUCN assessments were translated into the ICFARECC system as follows: "least concern" was equated to "-1", "near threatened" and "vulnerable" were translated into "0", and "endangered" and "critically endangered" were equated to "1". I scored species according to the IUCN criteria and the ICFARECC criteria (with and without IUCN) in order to compare their results. The subset of the ICFARECC criteria without the IUCN criteria was named IUCN-free ICFARECC.

2.6. Statistical Analysis

I used R studio ver. 0.98.1060 to establish the metabolic rate values, as well as to compare ICFARECC vulnerability scores to IUCN, and to make comparisons amongst the four categories. Correlations and p-values were calculated using the "rcorr" function in the 'Hmisc' library, using a Spearman's ranking due to the discrete nature of the data,

an alpha of 0.05 was chosen (Harrel Jr. 2016). The sample sizes at power = 0.8 were determined with the power calculator on the ANZMTG website (QFAB, 2017).

3. RESULTS

3.1. Selected Species

The selected species represented 6 orders, Clupeiformes, Gadiformes, Lophiiformes, Perciformes, Pleuronectiformes and Scorpaeniformes, and 11 families as shown in Table 2. The number of species in each family ranged from 1 (various families) to 5 (Pleuronectidae) and to 8 (Gadidae). The species were selected for this study based on catch biomass (Table 2). Some of the extremely high catch biomass measures, such as for herring (*Clupea harengus*), are due to long-term popularity in contrast to species that have only recently gained popularity, such as European hake (*Merluccius merluccius*). However, some species were excluded because data for multiple species within a genus had been combined (e.g., sandeels, *Ammodytes.spp.*). Some species were excluded because of lack of data, (e.g. witch flounder, *Glyptocephalus cynoglossus*), and some species were excluded because the species is no longer present in the North Sea (e.g. bluefin tuna, *Thunnus thynnus*). ICFARECC is not applicable to extinct species because the ecological assessment requires current population trends and the evolutionary potential Category requires local genetic data.

Table 2. Dominant North Sea fisheries species based on historic (1950-2010) catch data in ICES areas IIIa and IV (a, b + c). Catch data comprised by Eurostat and ICES (2011).

Common name	**Order**	**Family**	**Scientific name**	**Total catch biomass (tonnes)**
1. Atlantic herring	Clupeiformes	Clupeidae	*Clupea Harengus*	32347268
2. Norway pout	Gadiformes	Gadidae	*Trisopterus esmarki*	12160204
3. Atlantic mackerel	Perciformes	Scombridae	*Somber scombrus*	11559117
4. European sprat	Clupeiformes	Clupeidae	*Sprattus sprattus*	8772684
5. Atlantic cod	Gadiformes	Gadidae	*Gadus morhua*	8248506
6. Haddock	Gadiformes	Gadidae	*Melanogrammus aeglefinus*	7289819
7. European plaice	Pleuronectiformes	Pleuronectidae	*Pleuronectes platessa*	5794101
8. Whiting	Gadiformes	Gadidae	*Merlangius meluccius*	4596315
9. Blue whiting	Gadiformes	Gadidae	*Micromesistius poutassou*	2240532
10. Atlantic horse mackerel	Perciformes	Carangidae	*Trachurus trachurus*	2060971
11. Common sole	Pleuronectiformes	Soleidae	*Solea solea*	1142195
12. Ling	Gadiformes	Lotidae	*Molva molva*	640161
13. Anglerfish	Lophiiformes	Lophiidae	*Lophius piscatorius*	442983
14. Common dab	Pleuronectiformes	Pleuronectidae	*Limanda limanda*	403548
15. European hake	Gadiformes	Merlucciidae	*Merluccius merluccius*	385646
16. Lemon sole	Pleuronectiformes	Pleuronectidae	*Microstomus kitt*	299939
17. Tusk(=Cusk)	Gadiformes	Lotidae	*Brosme brosme*	194316
18. Grey gurnard	Scorpaeniformes	Triglidae	*Eutrigla gurnardus*	172005
19. European flounder	Pleuronectiformes	Pleuronectidae	*Platichthys flesus*	148197
20. European Seabass	Perciformes	Moronidae	*Dicentrachus Labrax*	88267

3.2. Extent of Data Availability

Over 250 articles were analyzed providing scoring for about 57% of all ICFARECC criteria. The number of scored criteria per species (Figure 1) varied from 93% in sole (*Solea solea*) to 37% in grey gurnard (*Eutrigla gurnardus*). More data was available for economically important species, such as sole (*Solea solea*), cod (*Gadus morhua*), and plaice (*Pleuronectes platessa*), than for bycatch species and those less economically important, such as grey gurnard (*Eutrigla gurnardus*) and lemon sole (*Microstomus kitt*).

The source and amount of data available varied in part by species. Extensive governmental report chapters were available for economically important species, e.g. cod (*Gadus morhua),* herring (*Clupea harengus),* mackerel (*Scomber scombrus)* and sole (*Solea solea),* and species with potential food web implications (e.g. Norway pout (*Trisopterus esmarki)* and haddock (*Melanogrammus aeglefinus);* piscivores). Population trend data was available for the aforementioned species and others in the yearly technical advice book published by ICES (2013). Direct population measures (e.g. SSB) were not reported or measured for certain species, e.g. bass (*Dicentrarchus labrax)* and blue whiting (*Micromestius poutassou*), in the Greater North Sea region.

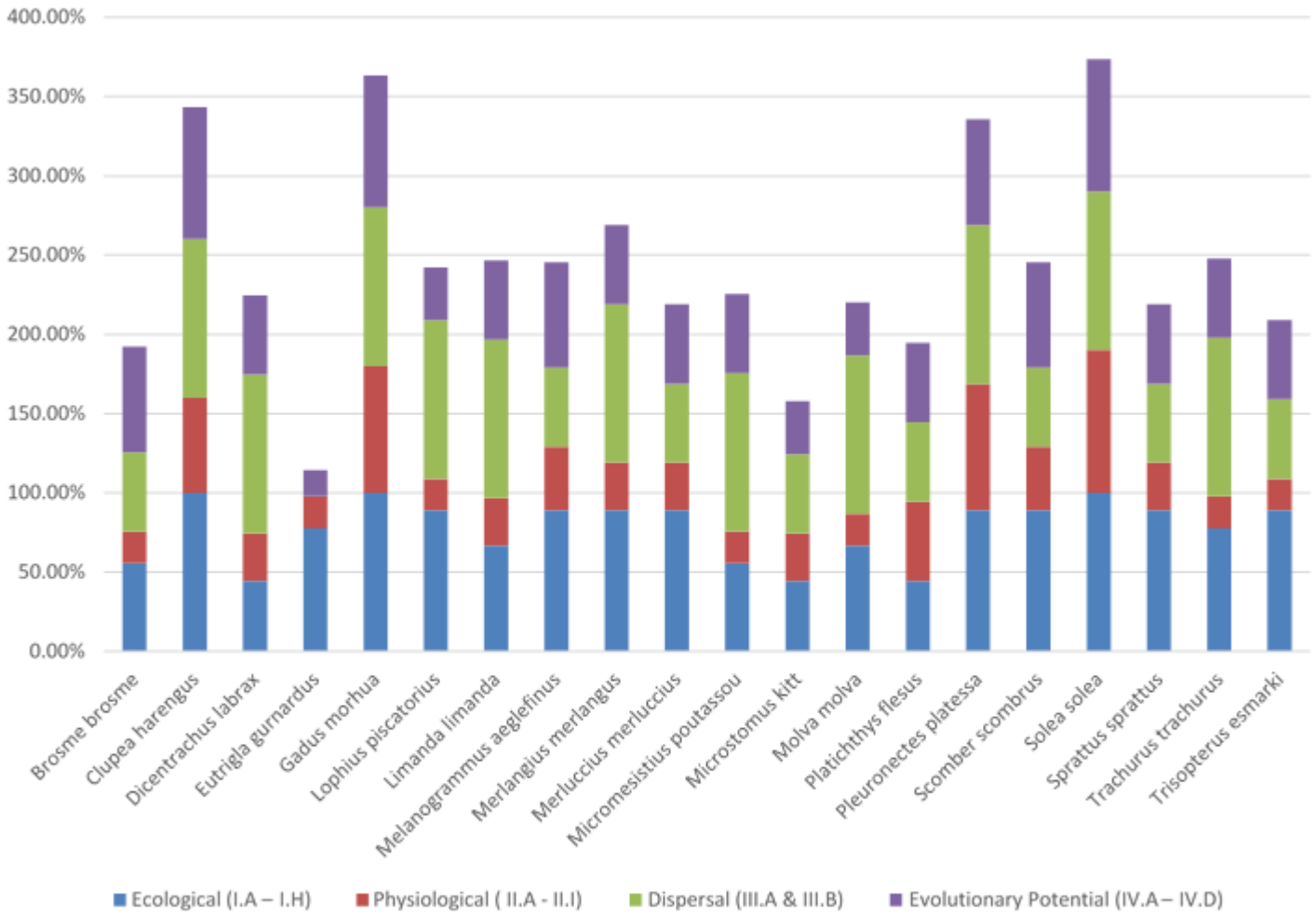

Figure 1. Percentage of criteria scored per species, including those adapted from the IUCN. A total of 27 criteria – All species scored total to 400%

Every species had some primary literature associated with it, but in some cases the data were from an invalid study site or were irrelevant for framework input. For example, the articles found for grey gurnard (*Eutrigla gurnardus)* were often compilation studies by ICES and other governmental agencies. The data for grey gurnard (*Eutrigla gurnardus)* from most primary literature were irrelevant to the study (e.g. Levsen and Karl, 2014; Moreno-Amich, 1994). Levsen and Karl (2014) studied parasitic nematode infection prevalence in grey gurnard. There is no specific place on the worksheet for data related to parasite occurrence and distribution. This makes the data irrelevant to my study. In contrast, data for sole (*Solea solea)* used in the ICFARECC approach came from wide-ranging studies largely focused exclusively on sole (e.g,.Walker et al., 1980; Witthames et al. 1995, Lefrancois and Claireaux, 2003, Cuveliers et al. 2012).

In addition, the source and timeliness of the data varied by ICFARECC Category (ecological, physiological, dispersal, or evolutionary potential). Data relating to Category III (dispersal) and Category IV (evolutionary potential, specifically IV.D life history traits) were often older, pre-2000 data. Category I (ecological) was most up-to-date. Additionally, most data was available for Category I (ecological) out of the 4 ICFARECC categories (Table 3; Figure 1). It was satisfied mostly through surveys of species occurrence and habitat occupancy, except for criterion I.E: modeled probability of extinction in the wild. The latter was the least scored criteria in the Category. The data for Category IV evolutionary potential were mostly derived from primary literature, and in some cases from published theses (e.g. cod (*Gadus morhua;* Svensson, 2009*).*

Table 3. Overview of the number of scored criteria per category. Most data was available for sole (*Solea solea*). The least amount of data was available for grey gurnard (*Eutrigla gurnardus*) and lemon sole (*Microstomus kitt*). Most data was available for Category I (ecological) and the least amount of data was available for category II (physiology).

Species	**common name**	**IUCN (I.A –I.E)**	**New ecological (I.F – I.H)**	**Physiological (II.A - II.I)**	**Dispersal (III.A & III.B)**	**Evolutionary Potential (IV.A – IV.D)**	**Total**
Eutrigla gurnardus	Grey gurnard	4	3	2	0	1	**10**
Microstomus kitt	Lemon Sole	1	3	3	1	2	**10**
Brosme brosme	Cusk /Tusk	2	3	2	1	4	**12**
Dicentrachus labrax	European bass	1	3	3	2	3	**12**
Micromesistius poutassou	Blue whiting	2	3	2	2	3	**12**
Molva molva	Common ling	3	3	2	2	2	**12**
Platichthys flesus	European flounder	1	3	5	1	3	**13**
Limanda limanda	Common dab	5	3	2	2	2	**14**
Lophius piscatorius	Monkfish	3	3	3	2	3	**14**
Trachurus trachurus	Atl. horse mackerel	4	3	2	2	3	**14**
Trisopterus esmarki	Norway pout	5	3	2	1	3	**14**
Merluccius merluccius	European hake	5	3	3	1	3	**15**
Sprattus sprattus	European sprat	5	3	3	1	3	**15**
Merlangius merlangus	Whiting	5	3	3	2	3	**16**
Melanogrammus aeglefinus	Haddock	5	3	4	1	4	**17**
Scomber scombrus	Atl. mackerel	5	3	4	1	4	**17**
Clupea harengus	Atl. herring	6	3	6	2	5	**22**
Pleuronectes platessa	Common plaice	5	3	8	2	4	**22**
Gadus morhua	Atlantic cod	6	3	8	2	5	**24**
Solea solea	Sole	6	3	9	2	5	**25**
	Total scored	**79**	**60**	**76**	**30**	**65**	**310**
	Total criteria	**120**	**60**	**200**	**40**	**120**	**540**
	Average	**0.66**	**1**	**0.38**	**0.75**	**0.54**	**0.57**

Data for criterion IV.B (genetic erosion (historical to recent times)) were only found for herring 23 (*Clupea harengus*), cod (*Gadus morhua*), plaice (*Pleuronectes platessa*), Atlantic mackerel (*Scomber scombrus*), and sole (*Solea solea*). The criterion IV.C related to genetic diversity within and across species, e.g. additive variance and heritability, was scored even less. Category II (physiological) was overall the least scored Category. This Category requires specific data related to a species' tolerance to (predominantly) temperature. Most of the temperature tolerance studies found related to temperature preference, not tolerance (e.g. Dulvy et al., 2008).

3.3. Summary of Vulnerability Scores

The overall scores among species are visualized in Figure 2 and were found to be on the spectrum between "not vulnerable" (-1) and "vulnerable" (0). The average score among the species assessed in this study was -0.62. Overall, ling (*Brosme brosme)* was found to be the most vulnerable species, scoring -0.27. The least vulnerable species, blue whiting (*Micromesistius poutassou*), scored -0.92. An average Order vulnerability was calculated for orders containing four or more species assessed in this study. Gadiformes and Pleuronectiformes were scored -0.55 and -0.62, respectively. This indicates that the Gadiformes are on average more vulnerable to climate change than the average species and Pleuronectiformes are on average less vulnerable. I did not find any evidence for a correlation between the final vulnerability score and the catch biomass (Figure 2).

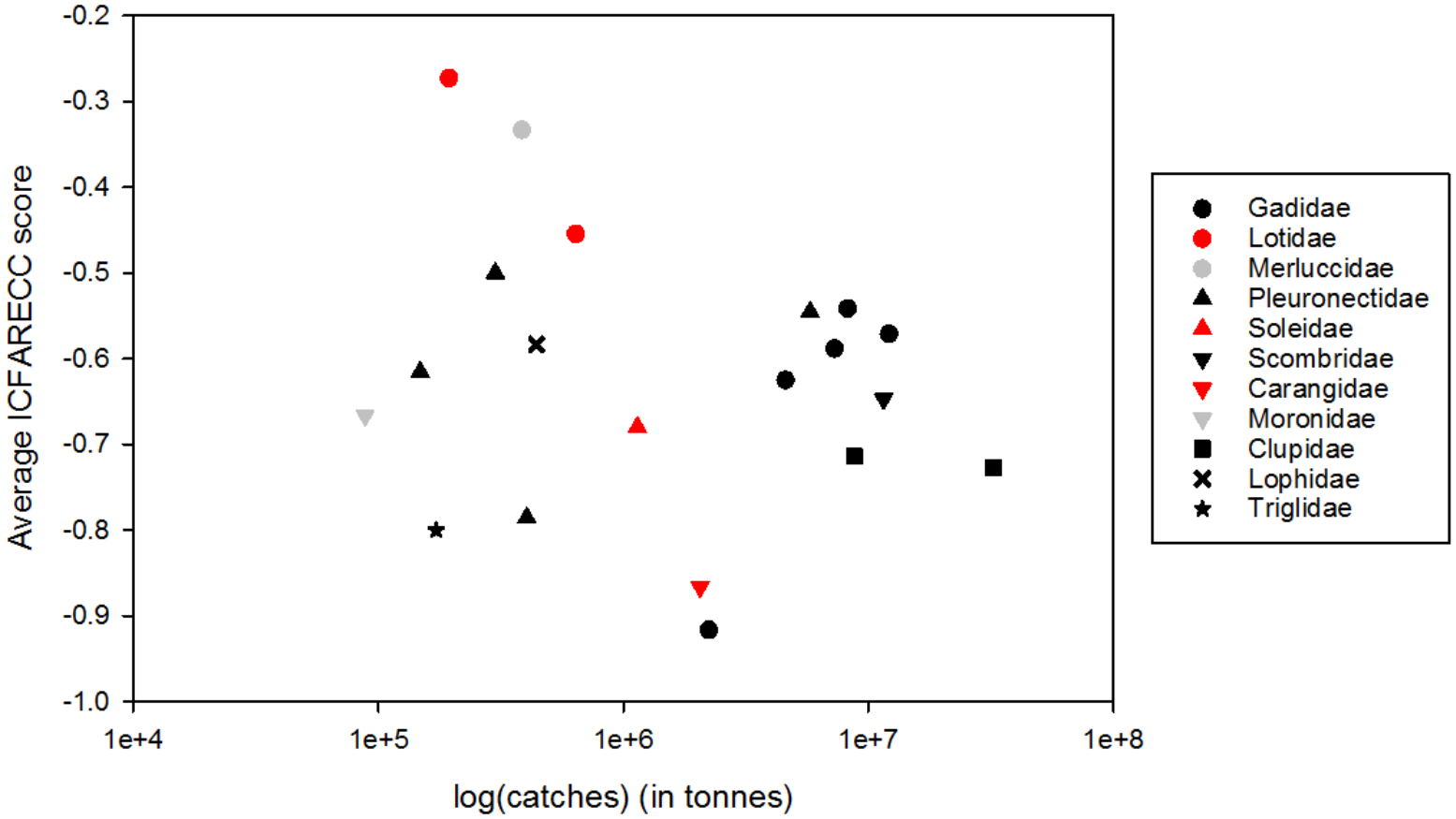

Figure 2. Average ICFARECC scores for studied species compared to catch volume.

3.4. Comparison of ICFARECC Scores and IUCN Scores

The IUCN derived criteria scores were compared to the overall IUCN-free ICFARECC scores and the individual new categories to determine whether these scores provide the distinct information. Cusk (*Brosme brosme*) was not part of comparisons for dispersal because no data were found pertaining to cusk dispersal. The IUCN criteria are a major component of Category I (ecological) of the ICFARECC criteria, so no comparison was made between them. No significant correlations were found between the IUCN criteria and the overall ICFARECC score ($r = -0.04$, $p = 0.88$). There were also no correlations between IUCN scores and the new categories or amongst the new categories (Table 4; $\alpha = 0.05$), indicating that each of the ICFARECC categories provides new information. Conclusions based upon the new criteria, therefore, do not appear to be redundant with those based on extant IUCN criteria.

Table 4. Overview of Category correlations coefficients. Correlation coefficients are located below the bolded diagonal line and P-values are located above the bolded diagonal. *IUCN*: criteria I.A. – I.E., *ICI*: ICFARECC criteria, excluding the IUCN criteria, *I*: (ecological) criteria I.A. - I.H., *II*: (physiological) criteria II.A. – II.I., *III*: (dispersal) criteria III.A. – III.B., *IV*: (evolutionary potential) criteria IV.A. –IV.D.

	IUCN	**ICI**	**I**	**II**	**III**	**IV**
IUCN	-	0.88	-	0.77	0.18	0.51
ICI	-0.04	-	-	-	-	-
I	-	-	-	0.83	0.41	0.31
II	0.07	-	0.05	-	0.72	0.41
III	-0.32	-	-0.20	-0.09	-	0.65
IV	0.16	-	-0.24	0.20	-0.11	-

4. DISCUSSION

This study assesses whether the newly developed ICFARECC framework is applicable to well-studied and strictly marine environments, evaluates limitations of the approach and suggests improvements, and additionally provides an indication of the vulnerability of the studied species. This study suggests some improvements to the framework, including adjustments to the terminology of criteria and thresholds and suggestions for a new format to make the framework more user-friendly.

4.1. Data Availability

Ecological data are the most available because this data can be collected simultaneously with other activities, e.g. population trend, and range occurrence and occupancy data can be collected or estimated during their exploitation. ICFARECC Category I (ecological) encompasses IUCN criteria in addition to criteria relating to ecological dependence and “altitudinal breadth”, which was interpreted as depth in my thesis. However, IUCN criteria were specifically developed to determine general vulnerability, especially in relation to human interference (Mace et al., 2008).

Physiological data by far were those least available. This can be explained by the lack of physiological data for marine fish in general and by the specificity of the criteria. Targeted temperature and performance studies are invasive in nature and difficult to conduct in fish, particularly form cold marine habitats. As a result, many studies (e.g. Dulvy et al., 2008) have focused on species distribution to infer species’ temperature

tolerance. However, habitats where species occur are not necessarily the only habitats a species can tolerate. These data are more likely to indicate species temperature preference than to indicate how a species' physiology may allow it to tolerate changing temperatures. This distribution of data availability will likely be different for terrestrial species and less exploited species. I'm not getting the point of this paragraph.

If a species is not able to tolerate its changing environment, or is not able to disperse to a suitable habitat, or is not able to evolve the capacity to improve tolerance or dispersal ability, it will go extinct. Various researchers have made extensive arguments for use of physiology as a powerful tool for forecasting extinction vulnerability (Stillman, 2003; Pörtner et al., 2005, Bernardo and Spotila, 2006, Helmuth et al. 2006, Bernardo et al. 2007, Pörtner and Knust 2007, Pörtner et al. 2008a, Farrell 2009, Somero 2010). Resources mentioned in the introduction of this paper emphasize the importance of physiology. The lack of physiological data may, therefore, have resulted in an underestimation of climate change vulnerabilities.

Although ICFARECC developers propose that, similarly to the IUCN assessments, not all criteria need to be assessed in order to form a conclusion, more data should still provide a more robust conclusion. My thesis and calculations show that each Category provides distinct information. This suggests that if no information was found for a particular Category of a particular species, the conclusion may be skewed. However, there is the possibility that the correlation was not found due to small sample size of this study, but the aforementioned conclusion is supported by previous uses of the framework. For example, the overall score calculated for Norway pout (*Trispterus*

esmarkii) was -0.57. However, if no information was found for Category IV (evolutionary potential), its score would have been -0.82. Alternatively, there is the possibility that no correlation amongst the ICFARECC was found due to small sample size of this study, but the distinctness of the categories is supported by previous uses of the framework The goal of the ICFARECC approach, unlike the IUCN approach, is to estimate how a species will react to climate change, whereas IUCN gives us insight into what the population trends are right now. If species' vulnerability as scored by ICFARECC is accurate, the lack of a particular Category will likely skew our understanding of a species' potential to respond to climate change.

4.2. The Applicability and Practicality of the Framework

In order to guide the user, the ICFARECC worksheet provides prompts for each criterion. In some cases, the terminology on the worksheet does not facilitate the applicability of the approach because some of the prompts are not very intuitive or complete. Past applications of the framework have been done by experts in the field. This method has been successfully applied to several other ecosystems, such as animals exploited for subsistence by Inupiat subsistence hunters in the Arctic (Kassam et al., in *prep*) and Appalachian salamanders (Bernardo, *in prep*). For example, the prompt for criterion III.H, Behavioral/phenological response, is "Is the species sessile, quiescent or mobile?" This prompt may restrict the user from providing data that relate to behavioral or phenological responses. Additionally, several ICFARECC criteria appear to be difficult to apply in marine systems. For instance, for Category IV (evolutionary potential section, criterion IV.C, relating to quantitative genetic diversity) measures of

heritability and additive variance in marine species are difficult to obtain. Law (2000) described the problem being the necessity that these measurements be made under the natural conditions at sea, which makes large-scale collection of heritability values challenging.

The strength of the framework, according to the developers is the objectivity of the assessments. This objectivity of the framework is reinforced when different people using this method obtain the same or similar results. However, some criteria lack a quantitative threshold and rely on personal interpretation, thus reducing overall objectivity of the framework. For this study, I attempted to develop some of these qualitative thresholds, but in some cases lacked the expertise or data to do so. Ideally, quantitative thresholds will be established similarly to the way the metabolic rate thresholds were established in this study, as described in the Methods.

4.3. Significance Of Results To NS Fisheries

This study indicates that overall key North Sea species would be near least concern. Common ling (*Brosme brosme)* scored lowest (-0.27) and is thus the most vulnerable out of the species studied. However, it is unclear what "least vulnerable" indicates in terms of, for example, the probability of extinction or major population decline. Though the species I studied are not likely to go extinct, it is reasonable to assume some species will experience a decline due to the combination of climate change stress and exploitation. Had species vulnerability and catch biomass been correlated, I might have been able to estimate an exploitation influence.

In fact, various researchers have already observed declining cod stocks due to the double threat of overfishing and climate change stress (O'Brien et al. 2000, Beaugrand et al. 2003, Clark et al. 2003, Edwards and Richardson 2004, Brander 2005, Pörtner et al. 2008a). Jennings et al. (1998) showed that certain life histories are more vulnerable to effects of exploitation. Thus, these species are also less likely to be tolerant or resilient to climate change (Bernardo et al., *in prep*; Perry et al., 2005). However, in exploited populations, it is especially hard to surmise whether certain trends are exploitation or climate change trends.

4.4. Recommendations

The assessment of species' climate change vulnerability in fish populations is complex because species' climate change vulnerability is affected by a multitude of environmental, physiological and genetic factors. ICFARECC aims to address these factors with the various criteria utilized in the framework. However, the framework is not effectively achieving its goal. The large amount of data needed for an effective application of ICFARECC was not present for all the species in this study. To be effective, there should be data for at least two criteria in each Category and 50% of the data scored to assign an overall species' vulnerability score. This would better validate vulnerability in general and give users better insight into the data that should be sought. Additionally, the framework might be most effectively used in the form of a web application, where each criterion is clearly explained and the user should answer an array questions that provide the application with the information needed to calculate a

final vulnerability score. This will only be possible after each criterion is provided with qualitative thresholds.

Framework developers should consider partnering with interested stakeholders, e.g. organizations like ICES or experts with potential unpublished data, to overcome the difficulty collecting requisite data. For example, ICES has commissioned and/ or funded many studies related to species in my North Sea assessment. Some of the assessments may not have been possible without their reports and commissioned studies. Many other organizations, e.g. NOAA, may be able to facilitate data collection for other assessments, e.g. Fish populations in the Gulf of Mexico.

Finally, validation of the framework through long-term assessments of wild populations or climate-change simulations would provide estimates that would aid interpretation of ICFARECC vulnerability scores. Insight into the contributions of the different ICFARECC categories to species' climate change vulnerability should be built into the framework and would allow for better justification of vulnerability scores when a considerable amount of the requisite data is unavailable.

5. CONCLUSION

Some species will be “winners” in the face of environmental change depending on their species’ traits, such as generation time, genetic variation, or population size (Somero, 2010). Some of these traits will enable them to be more tolerant, resilient or even prosper facing climate change. North Sea species likely will not be the winners in climate change, but there isn’t enough evidence to suggest they will be the losers. On the one hand, there was a lack of necessary data for certain species, and on the other hand, multi-species interactions are not taken into account. For a complete understanding of the possible outcomes of climate change, it is of vital importance that the aspects considered within the ICFARECC framework are considered in addition to potential food web or ecosystem interactions. However, there is a trade-off between how a model, or in this case framework, represents reality and the effortlessness with which it can be readily applied to any system. ICFARECC has a learning curve, but with the aforementioned adjustments, it has the potential to be a vital tool in assessing species’ vulnerability to climate change.

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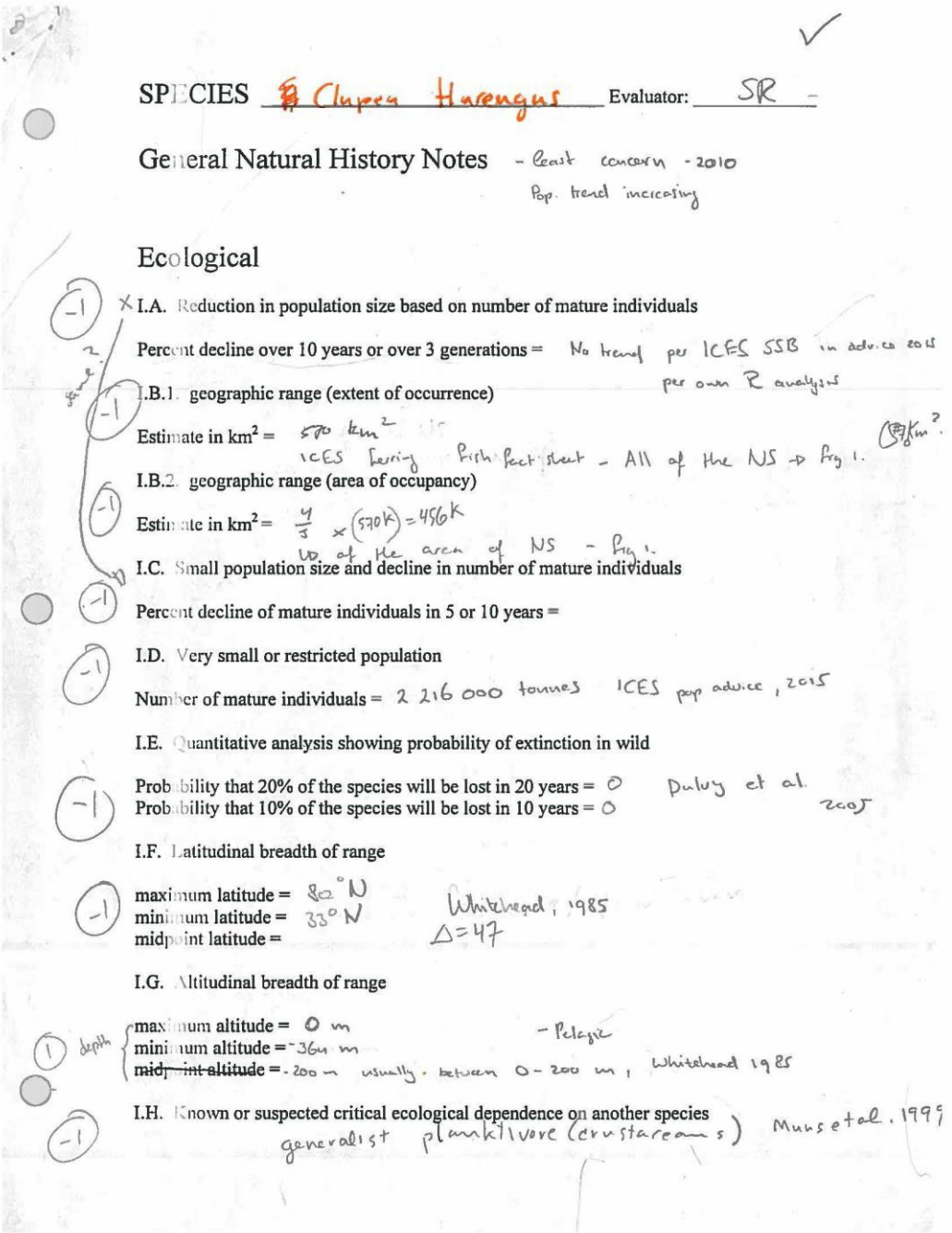
APPENDIX A

ICFARECC Worksheet Samples



SPECIES Clupea Harengus Evaluator: SR

General Natural History Notes - least concern - 2010
Pop. trend increasing

Ecological

-1 X I.A. Reduction in population size based on number of mature individuals

Percent decline over 10 years or over 3 generations = No trend per ICES SSB in advice 2015 per own R analysis

-1 I.B.1. geographic range (extent of occurrence)

Estimate in km² = 570 km² ICES Herring Fish Fact sheet - All of the NS → Fig 1. (570 000 km²)

-1 I.B.2. geographic range (area of occupancy)

Estimate in km² = 4/5 x (570K) = 456K 4/5 of the area of NS - Fig 1.

-1 I.C. Small population size and decline in number of mature individuals

Percent decline of mature individuals in 5 or 10 years =

-1 I.D. Very small or restricted population

Number of mature individuals = 2 216 000 tonnes ICES pop advice, 2015

I.E. Quantitative analysis showing probability of extinction in wild

-1 Probability that 20% of the species will be lost in 20 years = 0 Duluy et al. 2007
Probability that 10% of the species will be lost in 10 years = 0

I.F. Latitudinal breadth of range

-1 maximum latitude = 82° N
minimum latitude = 33° N Whitehead, 1985
midpoint latitude = Δ = 47

I.G. Altitudinal breadth of range

1 depth maximum altitude = 0 m - Pelagic
minimum altitude = -364 m
~~midpoint altitude~~ = -200 m usually between 0 - 200 m, Whitehead 1985

-1 I.H. Known or suspected critical ecological dependence on another species
generalist planktivore (crustaceans) Munsetal. 1999

Physiological

II.A. Tolerance Breadth

Optimum range: $T_{pejus\ (high)} - T_{pejus\ (low)}$ =
Critical (passive) range: $T_{crit\ (high)} - T_{crit\ (low)}$ =
Extreme range: $CT_{max} - CT_{min}$ = 20.1 − −1.25 = 21.35 from Portner & Peck, 2010 based on Blaxter 1960
Specify life stage: Larval 20 see II.E.2
Specify season: Average autumn / Spring spawners

II.B. Long-term thermal functional threshold (pejus) surpassed

ambient T_{mean} =
Period of daily mean T beyond low or high T_{pejus} =
% of time (day, season, year) beyond T_p: =

II.C. Short-term exposure to ambient extremes

ambient T_{max} (season) = ~17 Hunter et al 2004 (summer extreme) (worst case)
frequency of T_{max} beyond low or high T_{crit} or $CT_{min\ /\ max}$ = 0

II.D. Plasticity of long-term and critical thresholds

shift of T_{pejus} low / high between seasons / upon acclimation =
shift of T_{crit} between seasons / upon acclimation =
shift of $CT_{min\ /\ max}$ between seasons / upon acclimation = slight → Blaxter 1960 ~1C of Δ in upper lethal

II.E.1 Safety margin (long-term)

T_{pejus} =
$T_{hab\ mean}$ =
$T_{pejus} - T_{hab\ mean}$ =

II.E.2. Safety margin (short-term)

CT_{max} = 20 (23.85) Freitas et al. 2010 ← Too high based on lethals in Blaxter 1960 Braun 1960 larvae
$T_{extreme\ habitat\ value}$ = 17 extreme summer temp. ↳ ~22.0 ↳ ~19.78 Table 1 juveniles/adults.
$CT_{max} - T_{hab\ extreme}$ = (3)
Hunter et al 2004

II.F. Performance optimum

T_{opt} =
T_{hab} =
$T_{opt} - T_{hab}$ =

II.G. Magnitudes of environmental change across different variables

Percent increase in the frequency of heat waves =
Increase in average temperature = SST/NS 2070-2099 ↑ 1.9°C Pushpadas et al. 2009
Decrease in average rainfall =
Increase in average salinity =
Increase in salinity range =

II.H. Behavioral/phenological response
Is the species sessile, quiescent, or mobile?
Mobile, long-distance migrant, Carlen, 2002

II.I. Metabolic capacity (if aerobic).
Low temperature at which oxygen delivery to tissues becomes limiting =
High temperature at which oxygen delivery to tissues becomes limiting =

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* McPherson et al 2004

Dispersal

III.A.1. Indirect measures of dispersal

significant isolation by distance (IBD) ~~slope~~ = significant IBD p 249. Mariani et al, 2005
migration (Nm) =
number of well-supported haplotype groups =
F_{ST} = $\bar{x}$ of 11 allozyme loci = 0.014 André et al 0.027. Ruzzante et al, 2005 ≠ 9 msats
Φ_{ST} = -0.005 p7. Laakkonen et al 2013 ↑ REVISIT
F_{st} : 0.009 - Mariani et al. 2005 (Msat)

III.A.2. Direct measures of dispersal (radio-tracking, pollen capture, marking studies)
highly migratory eg well.
animal or plant movement estimate in sq km per time = larvae → 2.4 km/day Munk et al 1986

Genetics

IV.A.1. Overall genetic diversity of the species

Haplotype diversity (H_d) = 237/660 = .93-.98 Andre et al
Θ = .008 Bekkevold et al. 2005
π = 0.99 ± 0.13 Laakkonen et al 2013.
H_o/H_e (heterozygosity) = H_e microsat = 0.7-0.8 ?
H_e allozymes 0.12 - 0.14 Andre et al.

H_o 0.783 to 0.782
alleles = 15.9 to 12
Mariani et al. 2005

IV.A.2. Genetic diversity partitioned within the species over its distribution

number of individuals sampled = 660
number of alleles (average per locus) = 8.5-11.6 alleles/microsat locus p273 André et al
2-2.7/locus allozymes
number of haplotypes = 237
number of private alleles or haplotypes (restricted to one/few localities) =

IV.B. Genetic erosion from historical to recent history None to little Larsson et al 2010 Rockets Disc p96

$\pi - \Theta$ =
Skyline plot = increasing or decreasing since historical times

Slow - Tran et al 1999

IV.C.1. Overall quantitative genetic diversity across the species

heritability (h^2) =

additive genetic variance (V_A) =

evolvability (i) =

IV.C.2. Quantitative genetic diversity partitioned within species

Q_{ST} =

IV.D. Life history patterns

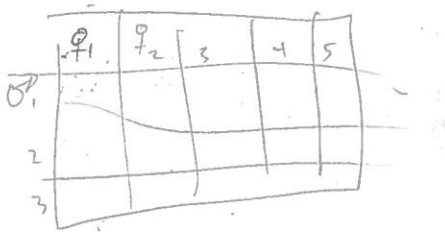
generation time =

effective population size =

clutch/litter size =

age at maturity =

Literature Cited



SPECIES Atlantic cod *Gadus morhua*

Evaluator: SR

IUCN – Vulnerable 1996 (needs updating)

General Natural History Notes

Ecological

(-1) I.A. Reduction in population size based on number of mature individuals

Percent decline over 10 years or over 3 generations = no decline - SSB, ICES advice Cod, 2015 per own regression analysis - R

(-1) I.B.1. geographic range (extent of occurrence)

Estimate in km² = 570k km²

(-1) I.B.2. geographic range (area of occupancy)

Estimate in km² = $\frac{164}{180} \cdot (570\text{ k km}^2) = 427.5\text{ k}$ Hedger et al 2004 Safe ethimate

(-1) I.C. Small population size and decline in number of mature individuals

Percent decline of mature individuals in 5 or 10 years =

(-1) I.D. Very small or restricted population

Number of mature individuals = 148 896 tonnes ICES pop advice, 2015

I.E. Quantitative analysis showing probability of extinction in wild

(-1) Probability that 20% of the species will be lost in 20 years = $\frac{0.2\%}{5}$ chance species will go extinct in 20 years Daly et al. 2015
Probability that 10% of the species will be lost in 10 years =

I.F. Latitudinal breadth of range

(-1) maximum latitude = 83° N
minimum latitude = 35° N → estimated from Cohen et al, 1990
midpoint latitude = (45)

I.G. Bathometric depth breadth of range

(0) maximum altitude = 0m Fishbase.org, 2/11/2016
minimum altitude = -600m → Cohen et al, 1990
midpoint altitude = -150 - 200m

up to 40m down Turner et al. 2002.

Physiological

II.A. Tolerance Breadth

Optimum range: $T_{pejus\ (high)} - T_{pejus\ (low)}$ =
Critical (passive) range: $T_{crit\ (high)} - T_{crit\ (low)}$ =
Extreme range: $CT_{max} - CT_{min}$ =
d.d. Specify life stage:
Specify season:

$\Delta t = 4.5$ preferred Dulvy et al. 2008

II.B. Long-term thermal functional threshold (pejus) surpassed

ambient T_{mean} = 17.0 °C Dulvy et al. 2008
d.d. Period of daily mean T beyond low or high T_{pejus} =
d.d. % of time (day, season, year) beyond T_p: =

II.C. Short-term exposure to ambient extremes

ambient T_{max} (season) =
d.d. frequency of T_{max} beyond low or high T_{crit} or $CT_{min\ /\ max}$ =

II.D. Plasticity of long-term and critical thresholds

shift of T_{pejus} low / high between seasons / upon acclimation =
d.d. shift of T_{crit} between seasons / upon acclimation =
shift of $CT_{min\ /\ max}$ between seasons / upon acclimation =

II.E.1 Safety margin (long-term)

T_{pejus} =
d.d. $T_{hab\ mean}$ =
$T_{pejus} - T_{hab\ mean}$ =

II.E.2. Safety margin (short-term)

CT_{max} =
d.d. $T_{extreme\ habitat\ value}$ =
$CT_{max} - T_{hab\ extreme}$ =

II.F. Performance optimum

d.d. T_{opt} =
T_{hab} =
$T_{opt} - T_{hab}$ =

II.G. Magnitudes of environmental change across different variables

Percent increase in the frequency of heat waves =
d.d. Increase in average temperature =
Decrease in average rainfall =
Increase in average salinity =
Increase in salinity range =

IV.C.1. Overall quantitative genetic diversity across the species

heritability (h^2) =
additive genetic variance (V_A) =
evolvability (i) =

IV.C.2. Quantitative genetic diversity partitioned within species

Q_{ST} =

IV.D. Life history patterns

Longevity = 12 years Rynsdorp et al. 1992
generation time =
effective population size =
clutch/litter size = 50 000 - 150 000 eggs Muus et al 1999
Age sexmat = males = 2-3 years; females = 3-5 years

Literature Cited